

Man-Machine Interface Issues in Space Telerobotics: A JPL Research and Development Program

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ABSTRACT

Technology issues related to the use of robots as man-extension or telerobot systems in space are discussed and exemplified. General considerations are presented on control and information problems in space teleoperation and on the characteristics of Earth orbital teleoperation. The JPL R&D work in the area of man-machine interface devices and techniques for sensing and computer-based control is briefly summarized. The thrust of this R&D effort is to render space teleoperation efficient and safe through the use of devices and techniques which will permit integrated and task-level ("intelligent") two-way control communication between human operator and telerobot machine in Earth orbit. Specific control and information display devices and techniques are discussed and exemplified with development results obtained at JPL in recent years.

1. INTRODUCTION

Current practice in robotics divides into two main areas: industrial robotics and robotic teleoperation. Industrial robots are used as an integral part of manufacturing processes and within the frame of production engineering techniques to perform repetitive work in a structured factory environment. The characteristic control of industrial robots is a programmable sequence controller, typically a mini- or microcomputer that functions autonomously with only occasional human intervention, either to reprogram or retool for a new task or to correct for an interruption in the work flow. Teleoperator robots, on the other hand, serve to extend, through mechanical, sensing and computational techniques, the human manipulative, perceptive and cognitive abilities into an environment that is either hostile to or remote from the human operator. Teleoperator robots or, in today's nomenclature, "telerobots" typically perform non-repetitive or singular, servicing, maintenance, repair or rescue work under a variety of environmental conditions ranging from structured to unstructured conditions. Telerobot control is characterized by a direct involvement of the human operator in the control since, by definition of task requirements, teleoperator systems extend or augment human manipulative, perceptual and cognitive skill which is far beyond what is obtainable with today's industrial robots. As a consequence, the human operator interface to a teleoperator or telerobot becomes a critical issue.

Continuous human operator control in teleoperation has both advantages and disadvantages. The main advantage is that overall task control can rely on human perception, judgement, decision, dexterity and training. The main disadvantage is that the human operator must cope with a sense of remoteness, be alert to and integrate many information and control variables, and coordinate the control of one or two mechanical arms each having many (typically six) degrees of freedom - and doing all these with limited human resources. Furthermore, in many cases like space and deep sea applications, communication time delay interferes with continuous human operator control.

Modern development trends in teleoperator control technology are aimed at amplifying the advantages and alleviating the disadvantages of the human element in teleoperator control by the development and use of advanced sensing and graphics displays, intelligent computer controls, and new computer-based man-machine interface devices and techniques in the information and control channels. The use of model and sensor data driven automation in teleoperation offers significant new possibilities to enhance overall task performance by providing efficient means for task-level controls and displays.

The purpose of this paper is to discuss and exemplify the technical issues involved in employing robots as man-extension or teleoperator systems in space. The primary space applications considered here are mechanical operations in Earth orbit. These include the deployment, servicing, maintenance or retrieval of satellites, the handling and assembly of structural elements for creating space station or other large space structures, and the maintenance or repair of finished and operational space systems.

General considerations are presented in Section 2 related to: (i) characteristics of earth orbital environment from the viewpoint of remote robot control, (ii) control and information problems in remote operations of robots with emphasis on human factors involved in the information-control loop, and (iii) data driven automation. Specific control techniques are discussed in Section 3 suited to make efficient use of human command and control capabilities in task-level controls. Techniques and examples are presented in Section 4 aimed at integrated and task-level displays of multidimensional sensory information to aid control decisions.

2. GENERAL CONSIDERATIONS

The use of robots as man-extension or teleoperator systems in Earth orbit requires two major considerations. The first is related to the specifics of structures and environment in Earth orbit, the second is related to the generic nature of operating robots as multi-degree-of-freedom mechanical systems in performing dexterous tasks.

2.1 Teleoperation in Earth Orbit

A number of specific conditions must be considered for teleoperation in Earth orbit. First, the objects to be handled by robot arms are typically large or extended objects. The manipulation of large objects by robot arms typically requires the specification and observation of widely separated contact points between object and environment. Second, the structural elements in Earth orbit are typically composed of light materials having low specific mass. But the ratio of the robot arm's inertia versus the manipulated object's inertia can vary by orders of magnitude. Third, the weightless environment in Earth orbit removes the directional effect of gravity. In zero gravity, dynamically defined "up" and "down" do not exist; things do not "drop down"; contact between objects and environment must be established by the robot arm's controller actively. Fourth, the visual conditions in Earth orbit -- short "day and night" periods, non-diffuse light, highly disparate backgrounds for viewing work scenes, etc. -- impose a number of operational constraints. Fifth, dependent upon the physical distance between control station and robot in Earth orbit, various communication bandwidth or communication time delay constraints may exist which have an effect upon control and information system design and performance.

2.2 Information and Control Complexity

Task-level control of robot arms requires the coordinated motion or force control of several (typically six) robot arm joints while observing a variety of kinematic, dynamic and environmental constraints. Then, to comply with the specifics of a given task, different sensor signals must be interpreted in real time. Furthermore, manipulation tasks can often be performed in different ways. Hence, robot arm task-level control implies a multilevel decision and monitoring process at both the control input and information feedback channels.

It is known that the human operator's input and output channel capacities are not only limited but also asymmetric; the human has much more information receiving (input) channels than information conveying (output) channels. In this sense, the human operator represents a limiting factor in the complex information and control environment of a remotely operated robot. Following this recognition, the general objectives of control, information and man-machine interface development for space robots as man-extension systems are: Provide devices and techniques which enable the human operator to convey control commands to and receive control feedback from the remotely operated robot in comprehensive, integrated and task-level terms and formats.

2.3 Data Driven Automation

Data driven automation here refers to the use of models and sensing sources through computers in the control of remotely operated robots. Data derived from models typically provide a priori information about robot machines and tasks. Data derived from sensing sources typically provide on-line information about robot task performance. Data driven automation is inherently flexible since it is programmable. It contrasts the mechanically fixtured, rigid or fixed automation.

Application of robots in space as man-extension systems requires flexibility in both control and information management in order to cope efficiently with varying and unpredictable task conditions. The use of data driven automation offers significant new possibilities to enhance overall task performance by providing programmable devices and techniques for task-level controls and displays.

3. CONTROLS

Computer controls based on robot arm and task models and on information from sensors integrated with the robot arm's end effector permit the development of new devices and techniques which enable the operator to exercise control commands in comprehensive task-level terms. Computers also allow the use of voice as a new communication channel in controlling elements of remote robot systems.

3.1 Interactive Sensor Referenced Manual-Automatic Control

Interactive control signifies here a hybrid control capability which allows that some motions of the remote robot arm in work space coordinates are under manual control while the remaining motions in the same work space reference frame are under automatic computer control based on sensor information originating from the robot end effector. It is noted that, in this hybrid control system, the manual control is in task-level terms, using resolved rate controls, which also require a computer in the control system. The sensor-referenced automatic controls are also in task-level terms defined within a pre-programmed control menu.

A pilot computer control system has been implemented at JPL for a six-degree-of-freedom robot arm the end effector of which is equipped with proximity and force-torque sensors. The sensors and the implementation details of this pilot control system are described in Refs. 1 and 2. The general system configuration together with the manual and computer control panels are shown in Fig. 1. The manual control is normally in resolved rate or resolved position mode, using the appropriate computer control algorithms to interpret two three-degree-of-freedom joystick inputs. A preprogrammed sensor-referenced automatic control menu is available to the operator who decides on-line when and which automatic control function should be activated or deactivated. Each automatic control function selection can be accomplished by turning a simple on-off switch addressed directly to the control

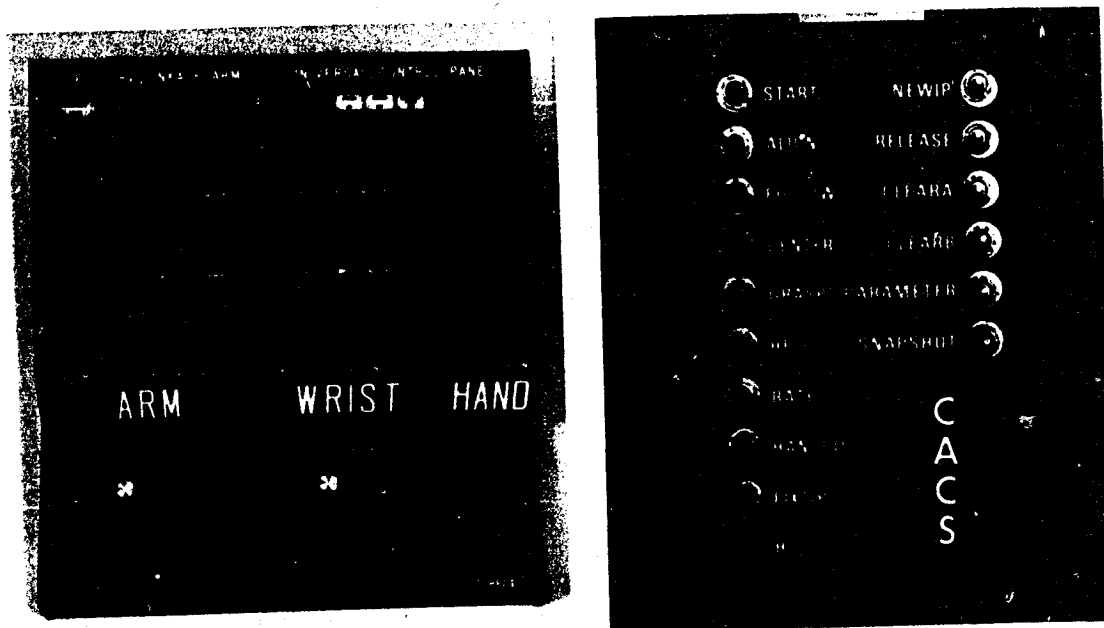
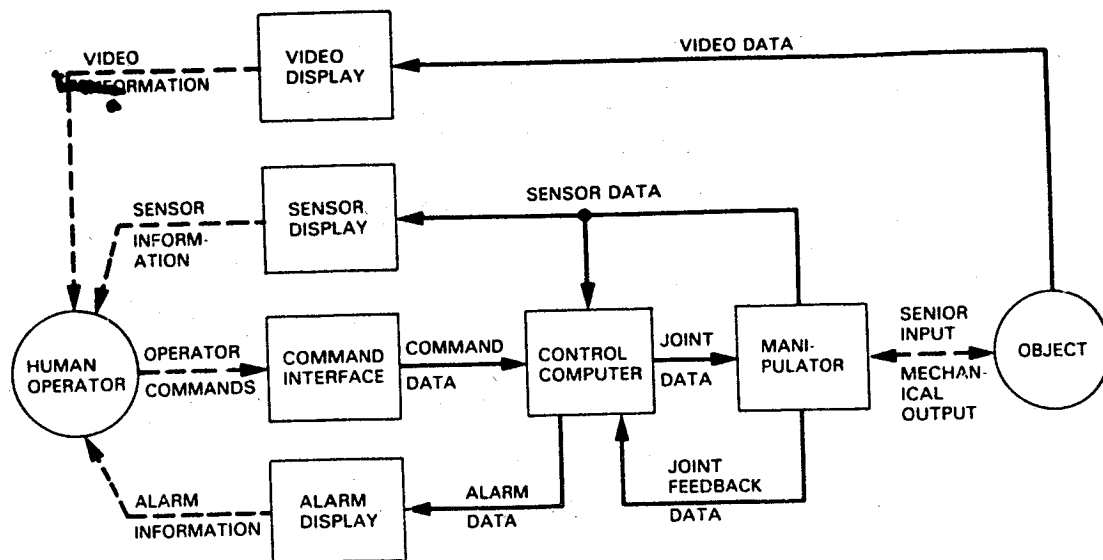


Fig. 1. Overall system implementation of interactive hybrid manual-automatic control referenced to sensors.

computer. Some parameters of the automatic control menu can be changed on-line. Note that, in this hybrid control system, the operator has a dual (analog/continuous and digital/discrete) communication with the control computer. Note also that, in extreme cases, all control can be either fully manual control or fully automatic control referenced to sensors.

The structure of the interactive control system software is built on a design concept which states that particular manipulator tasks can be considered as arrangements of interconnected actions which are enforced directly by the operator's continuous manual inputs or by automatic computer control algorithms. In order to synthesize the automatic control of interconnected complex actions, three action categories -- primitive, composite and complex actions -- have been introduced. Primitive actions include elementary motions (e.g., one-step shifts of the mechanical hand) in a given task frame, etc. Composite actions are composed of several primitive actions which are executed sequentially. (E.g., align the mechanical hand relative to a surface.) Complex actions consist of composite actions which are executed sequentially or in parallel. (E.g., follow a moving object.) Execution of a complex action is determined by precedence rules that define the order of execution of the corresponding composite actions. These rules also specify the conditions that must be satisfied to start or to terminate the execution of the actions. These rules can be expressed graphically by diagrams called Action Precedence Graphs. More on this can be found on Ref. 2.

The main purpose of this pilot development project was to study and evaluate the control hardware and software performance implications of interactive manual and automatic control in teleoperation. Some of the main conclusions are: (i) logic decision nets are the dominating elements in this type of control, and their implementation requires special care; (ii) the capability of executing both manual and automatic computer controls within the same task, function and action formulation frames facilitates the operational integration of human and machine logic in teleoperator control.

3.2 Generalized Bilateral Manual Control

In bilateral, force-reflecting manual control the operator feels the forces and torques acting at the remote robot hand while he manually controls the motion of the robot hand through a master input device which is called the "master arm". In the existing industry practice, the master arm is a one-to-one size replica of the remote slave arm, and each slave arm must have its own master arm. In most cases the master arm is mechanically coupled to the slave arm. This is the standard practice in the nuclear industry. Only in a few cases is the coupling implemented electromechanically through bilateral servo control.

A limiting factor for broadening the application of bilateral force-reflecting robot control technology is the nature of the master arm. To overcome this limitation, a new form of bilateral, force-reflecting manual control has been implemented at JPL recently. It utilizes a general purpose force-reflecting hand controller (Ref. 3). The hand controller is a six-degree-of-freedom control input device that can be back-driven by forces and torques sensed at the base of the end effector of a remote robot arm. This hand controller is general purpose in the sense that it does not have any geometric and dynamic similarity to the slave arm it controls; it is not a replica of any slave arm, but it can be coupled to and used for the control of any remote slave arm.

The positional control relation between the general purpose hand controller and a remote robot arm is established through mathematical transformation of joint variables measured at both the hand controller and robot arm. Likewise, the forces and torques sensed at the base of the remote robot hand are resolved into appropriate hand controller motor drive commands through mathematical transformations to give to the operator's hand the same "feeling" that is "felt" by the remote robot hand (Ref. 4). The complex bilateral mathematical transformations are performed by a dedicated minicomputer in real time. These transformations also effect motion synchronization between hand controller and slave arm, referenced to the slave hand, by backdriving the hand controller. Overall system implementation is shown in Fig. 2. A preliminary control system analysis and synthesis of this system can be found in Ref. 5. Some experimental results are presented in Ref. 6.

The new form of bilateral manual control of remote robot arms described here generalizes the force-reflecting manipulator control technique. This type of control provides a kinesthetic coupling between operator and remote robot arm, and can be considered as a combination of "body language" and "reflexive feedback" with some basic communication primitives as indicated in Fig. 3. Note that these primitives allow task-level control. Through kinesthetic coupling the operator can command with "feel" and control with a "sense of touch."

Laboratory experiments are currently conducted at JPL to determine the effect of weightlessness of the human arm on this control mode when the operator is located in Earth orbit. Some preliminary results of these experiments are described in Ref. 7.

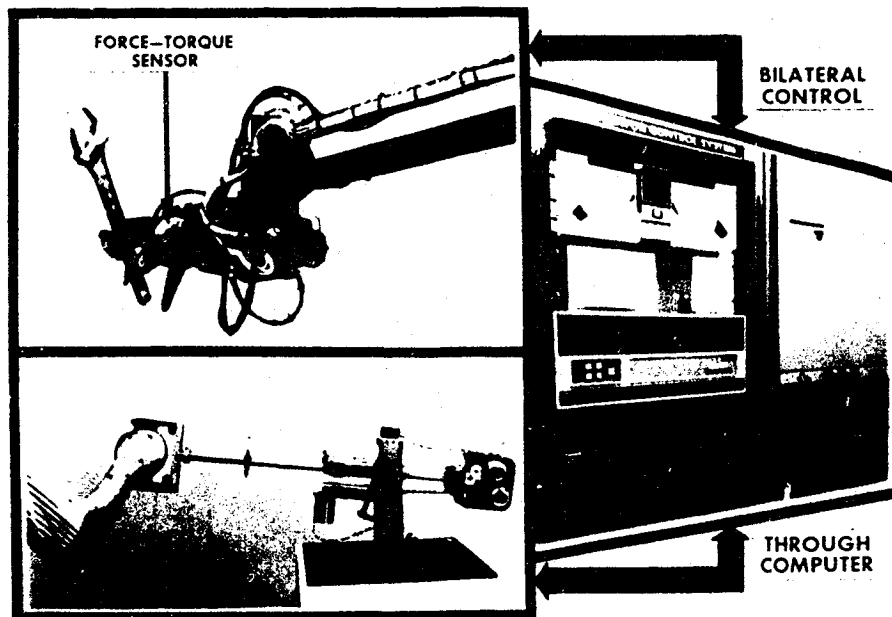


Fig. 2. Overall system implementation of generalized bilateral manual control.

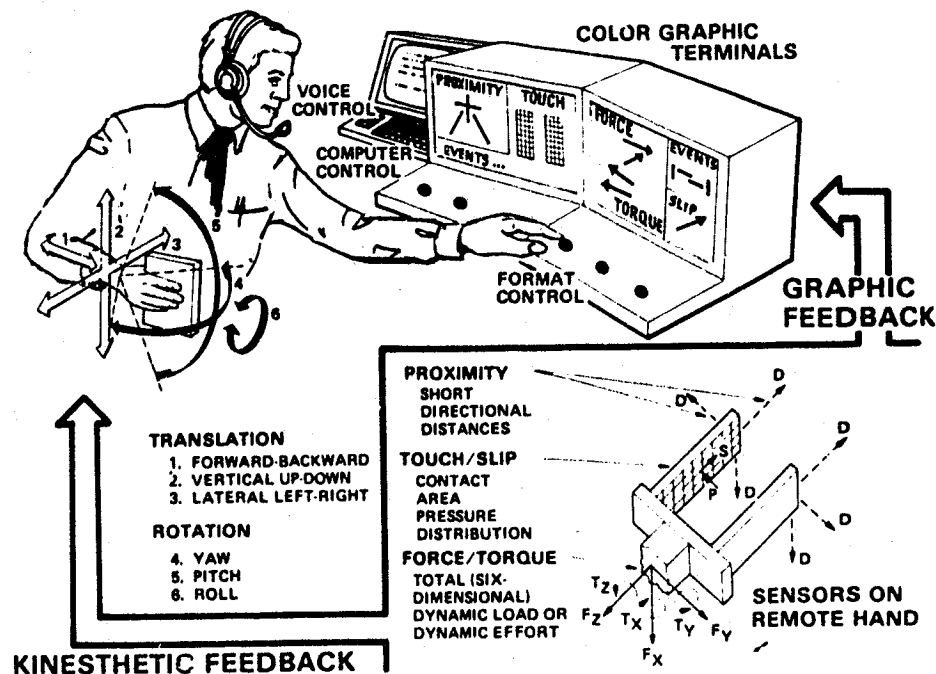


Fig. 3. Integration of graphics, kinesthetic, computer and voice man-machine interfaces.

3.3 Voice Control

The use of voice commands to control machines offers a new communication channel which is open and within reach most of the time and does not require manual or some specific visual contact between operator and machine.

Advancements in computer-based discrete word voice recognition systems make the direct use of human speech feasible for control applications in a teleoperator control station. Several such applications have been developed at JPL (Ref. 8). The latest application system was developed for the control of the Space Shuttle TV cameras and monitors while the operator manually controls the Shuttle robot arm. In this application the operators could "push" control switches by voice instead of using fingers. Some Shuttle robot arm tasks are visually very demanding, and can require 50 to 70 commands to four TV cameras and two TV monitors within 15-20 minutes time frame to assure sufficient visual feedback to the operator. The ground control tests at the Johnson Space Center (Ref. 9) have shown 96 to 100% voice recognition accuracy for the best test runs and resulted in the following major conclusions: (i) the application concept is realistic and acceptable; (ii) the use of voice commands indeed contributes to a better man-machine interface integration; (iii) individual human acoustic characteristics and training have a major impact on system performance.

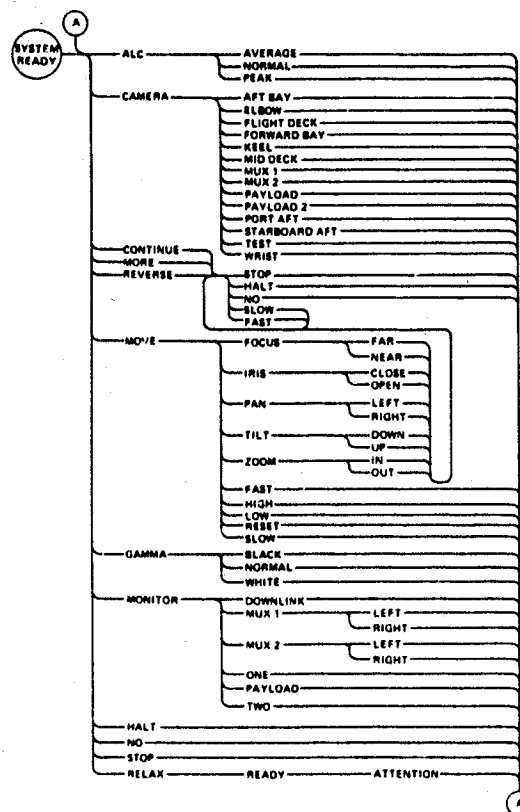
Several alternative combinations of control vocabulary words with and without syntax restrictions were developed and tested. Altogether thirty-six control switches had to be activated by voice commands. The training experiments have shown that the operators prefer simple vocabularies with minimum or no syntactic restrictions. To cope with this desire, vocabularies were constructed using concatenated words for full action commands. The most successful vocabulary is shown in Fig. 4. It has no syntax, uses concatenated command words, and contains only two simple words ("stop" or "reverse") which logically must follow some action commands. Compare the simple vocabulary to the vocabulary with syntax that also is shown in Fig. 4. As it turned out, the operators remembered and used with higher confidence buzz-word-like voice commands than words which were embedded into syntactic procedures.

4. DISPLAYS

The use of both visual and nonvisual sensor information is required for successful control of the robot arm's geometric and dynamic interaction with objects and environment. Visual information is obtained through direct vision or TV and can be supplemented or "sharpened" with information from ranging devices. The visual information for teleoperator control is essentially geometric, related to the manipulator's gross transfer motion and to the position/orientation control of the end effector.

The nonvisual sensor information supplements the visual information and is related to the control of the mechanical hand's contact or near-contact with objects and environment. The nonvisual sensor information provides a combination of geometric and dynamic reference data for the control of terminal position/orientation and dynamic accommodation/compliance of the mechanical hand. Non-visual information related to robot arm control can be obtained from proximity, touch, slip, and force-torque sensors integrated with the robot arm/hand as illustrated in the lower right part of Fig. 3. More on these sensors and their applications can be found in Ref. 1.

WITH SYNTAX



WITHOUT SYNTAX

PORT-FORWARD	AFT-PORT			MONITOR-1	
FORWARD-PORT	PORT-AFT			MONITOR-2	
AFT-STARBOARD	FORWARD-STARBOARD			MUX-1-LEFT	
STARBOARD	STARBOARD-FORWARD			MUX-1-RIGHT	
MUX-1	RMS-PORT			MUX-2-LEFT	
MUX-2	ELBOW			MUX-2-RIGHT	
RATE-HIGH	FOCUS-FAR	ZOOM-IN	IRIS-OPEN	TILT-UP	PAN-LEFT
RATE-LOW	FOCUS-NEAR	ZOOM-OUT	IRIS-CLOSE	TILT-DOWN	PAN-RIGHT
	REVERSE			STOP	
PEAK	ALC-NORMAL	AVERAGE	WHITE	GAMMA-NORMAL	BLACK
RELAX	READY	ATTENTION			

Fig. 4. Voice command vocabulary for TV camera/monitor control, using words with syntax and concatenated words without syntax.

Graphics displays of proximity, touch, slip, and force-torque sensor information transform non-visible or hardly-visible events into visually perceivable forms on a graphic terminal. Graphics displays of sensor information can be used in both manual and computer control modes. In a manual control mode the displays are elements in the continuum of a real-time control loop in the sense that they guide the operator's continuous control input by providing continuous information feedback on the appropriate "external error state" of the robot hand. In a computer control mode, the displays represent discrete elements outside the real-time control loop. They provide information to the operator prior to the selection and initialization of an appropriate sensor-referenced computer control algorithm, and inform the operator about the performance of the control algorithm selected for the task at hand.

The stream of data generated by sensors on a "smart hand" (proximity, touch and force-torque sensors) provides multidimensional information, and requires a quick (sometimes split-second) control response. In general, the control decision required to respond to the data is also multidimensional. This represents a demanding task

and heavy workload for the human operator. It is also recognized that the use of information from sensors on a "smart hand" often requires coordination with visual information.

4.1 Event Driven Displays

Event-driven displays can considerably sharpen the information content of multidimensional sensor data and thereby aid the operator's perceptive and decision making task.

By definition, event-driven displays map a control goal or a set of subgoals into a multi-dimensional data space based on the fact that control goals or subgoals always can be expressed as a fixed combination of multi-dimensional sensory data. Event-driven displays can be implemented by real-time computer algorithms which (i) coordinate and evaluate the sensory data in terms of predefined events and (ii) drive the graphics display. Flexible display drive algorithms require a variable set of task oriented parameters specifiable by the operator in order to match the specific needs of a given control task. (Ref. 10)

An event driven "smart" display system, developed at JPL, is shown in Fig. 5 together with the proximity sensor system which generates the sensory data to be displayed. The figure also shows the measurement definitions. The purpose of the "smart" display is to show the operator the values of range, pitch and yaw errors referenced to end effector axes, and also to indicate whether the combination of these three errors will allow a successful grasp of the target. (Ref. 11)

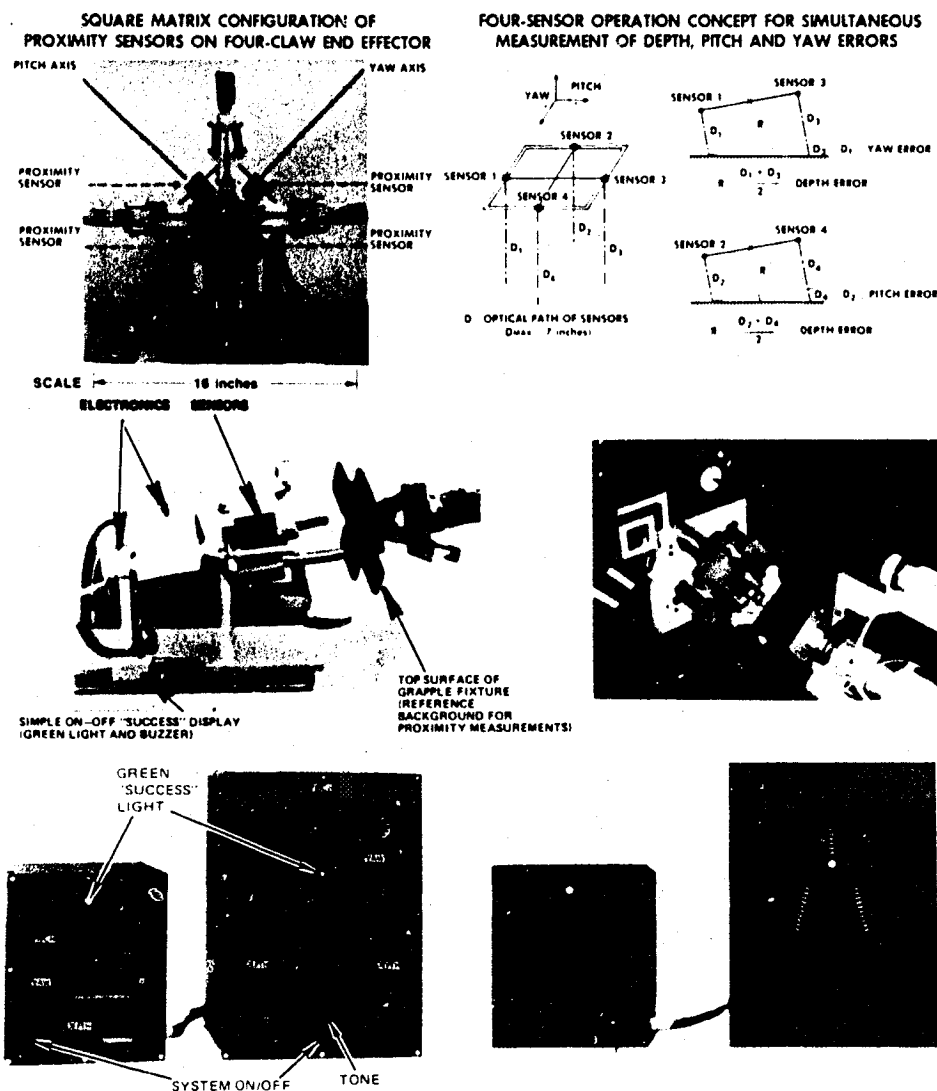


Fig. 5. Proximity sensor system with "smart" event driven display for space shuttle robot arm application.

The graphic display has been built from 10-element linear LED displays encapsulated in one chip, with individual addressable anode and cathode for each element in the chip. The graphic display resolution is 0.2 inches (0.508 cm) per display element in depth, and 1 degree per display element in pitch and yaw errors. The quantitative value of each error for each bar is increasing away from the center green lamp. Hence, zero error for each bar is at the center of the display. This focuses the operator's attention to a single "goal point" on the display towards which all error bars should be decreased and where the event indicator "green light" should be on for successful grasp.

Note that depth error is indicated with two identical bars converging in a parallax-type view arrangement towards the center green lamp. This renders the display more symmetric and facilitates the distinction between angular and depth-error bars. The green light "on" condition indicates that the existing combination of depth, pitch and yaw errors will allow a successful grasp.

The graphic display also contains a tone generator. It provides a "warning tone" (a short beep tone) when the target reaches the sensing range or leaves the sensing range. The maximum depth sensing range shown on the display is 6 inches (or 15 cm). Pitch and yaw errors are indicated in the range of ± 15 deg.

The numeric display resolution is 0.1 inches (0.254 cm) in depth error and 0.5 deg in angular errors. It also has the "green success lamp".

The "smart" event-driven displays are controlled by a single board Intel 80/20 microprocessor which linearizes the sensor data and processes the linearized data through a preselected "success algorithm". An appropriate "success algorithm" can be selected in the computer through a switch. The algorithms can be referenced to alternative roll orientations of the end effector pitch and yaw axes, and can utilize alternative numeric definitions for "successful grapple envelope" in terms of maximum and minimum values of allowable depth, pitch and yaw errors.

4.2 Event Controlled Displays

Event-controlled displays extend the capabilities of event-driven displays by automatically effecting changes between data displays and data formats on a graphics monitor.

The need for different types of sensor data displays or for different formats of data displays typically arises in a logical sequence in remote robot control tasks. For example, when proximity sensor data are needed then normally there is no need for touch or force-torque sensor data, or vice versa. This sequential logic in the need of sensor information can be utilized to switch automatically between different data displays or formats. Following this concept, event-controlled displays have been implemented at JPL (Ref. 12). In the implemented examples predefined changes in sensor data automatically effect changes in display modes, formats and parameters, matching the need for a particular information to different phases of the task. Event-controlled displays require the implementation of state transition nets in real-time computer programs based on event detection logic.

Event controlled or automatic display mode/format switching can alleviate much of the display control workload for the operator.

5. CONCLUSIONS

Automation in teleoperation is distinguished from other forms of automated systems by the explicit and active inclusion of the human operator in system control and information management. Such active participation by the human, interacting with automated system elements in teleoperation, is characterized by several levels of control and communication, and can be conceptualized under the notion of "supervisory control" as discussed in Ref. 13. The man-machine interaction levels in teleoperation can be considered in a hierarchic arrangement as outlined in Ref. 14: (i) planning or high level algorithmic functions, (ii) motor or actuator control functions, and (iii) environmental interaction sensing functions. These functions take place in a task context in which the level of system automation is determined by (a) the mechanical and sensing capabilities of the telerobot system, (b) real time constraints on computational capabilities to deal with control, communication and sensing, (c) the amount, format, content and mode of operator interaction with the telerobot system, (d) environmental constraints, like task complexity and (e) overall system constraints, like operator's skill or maturity of machine intelligence techniques.

Some advances have been made in teleoperator technology through the introduction of various sensors, computers, automation and new man-machine interface devices and techniques for remote manipulator control. The development of dexterous mechanisms, smart sensors, flexible computer controls, intelligent man-machine interfaces, and innovative system designs for advanced teleoperation is, however, far from complete, and poses many interdisciplinary challenges (Refs. 15-17). It should also be recognized that the normal manual dexterity of humans is more a "body" skill than an intellectual one. The man-machine interface philosophy embodied in the force-reflecting master-slave manipulator control technology has been founded mainly on this fact. Advanced teleoperation employing sensor-referenced and computer-controlled manipulators shifts the operator-telerobot interface from the body (analog) level to a more intellectual language-like (symbolic) level. Research efforts for developing new man-machine interface technology for advanced teleoperation will have to render the language-like symbolic interface between human operator and telerobot as efficient as the conventional analog interface. This remark also applies to operator interface development for procedure execution aids and for expert systems in teleoperator action planning and error recovery.

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